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140-20 Keyland Court
Business Address: Bohemia, New York 11716

Principal Investigator, Dr. Rama Rao
Project Scientist or
Engineer

Effective Date of Contract: August 31, 1988

Phone Number: (516) 563-7067

Contract Expiration Date: Feb., 28, 1989

Short Title of Work: High Tc Superconductor
Detector Fabricated with Y-Ba-Cu-O

Reporting Period: Aug.31, 1988- Feb.28, 1989

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DEFENSE ADVANCED RESEARCH PROJECT AGENCY
PHASE I SBIR
FINAL REPORT
 (Aug..31, 1988—Feb.28, 1989)

Institution

Excel Technology, Inc.
 140-20 Keyland Court
 Bohemia, New York 11716
 (516) 563-7067
 Attn: Dr. Rama Rao

Project Title:

Highly Sensitive Infrared
 Detector fabricated with
 Thin Film of High Tc
 Y-Ba-Cu-O Superconductor.

Contracting Officer

Mr. Dennis Elenburg/
 Dr. Charles Pines
 U.S. Army Missile Command
 AMSMI-PC-BFA/DARPA
 Redstone Arsenal,
 Alabama 35898-5280

Contract No.

DAAH01-88-C-0748



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Abstract

In the phase I study of the project entitled "Highly Sensitive Infrared Detector Fabricated with Thin Film of High Tc Y-Ba-Cu-O Superconductor using Pulsed Laser", we have (Contract No. DAAN01-88-G-0748), we have successfully deposited thin films of Y-Ba-Cu-O on MgO/TrO2 substrate by plasma assisted laser deposition (PLD) technique. One great advantage of PLD method is that precisely controlled as-deposited thin film of desired stoichiometry can be prepared at low processing temperature (450 degree C) without the need of any post annealing. High temperature post annealing tends to percolate microcrystals which renders the optical excitation highly inhomogeneous for optical detection studies. Based on these results, a paper has been submitted for the presentation at CLEO'89 to be held at Baltimore from April 24-28, 1989 (Please See Appendix A).

Subsequent to deposition, the film was patterned to form a 20 μm wide superconducting microbridge by laser induced etching technique. The pattern is done by a CW, Q-switched, frequency-doubled Nd:YAG laser operating at 532 nm at 1 KHz. In order to increase the sensitivity of the detector, a "zig-zag" shape pattern of 20 μm wide, 0.3 μm thick, and 25-cm long was made on a superconducting film on ZrO2 substrate. In a preliminary detection experiment, using 100 nsec laser pulses at 532 nm, two components were measured in the voltage response, slow response at transition temperature due to bolometric effect, and a fast response below transition temperature, due to Cooper pair breaking and quasiparticles generation. Several groups have observed bolometric response on these films but none of them have been successful yet in detecting quantum response. This is the first observation of fast non-thermal optical response in these types of films. Based on these results, a paper has been presented at the March meeting of American Physical Society (Please see Appendix B).

Our results have indicated that thin films that were optically semitransparent are crucial in the observation of fast nonthermal response. Thus in the subsequent experiments, smooth, transparent 80 nm thin films were made. Depending on the film thickness and the deposition condition, Tc could vary from 41°K to 82°K. Preliminary results showed that the low Tc films provided better optical response. This time 1.06 μm infrared beam with 6 nsec pulse duration was used for optical detection. Again, two components were measured in the voltage response. The temperature dependence of these two components indicated different thermal and non-thermal behaviour. The speed of non-thermal quantum component was limited by the 6 nsec laser pulse duration. This work is the first demonstration of non equilibrium optical detection made in these new class of high temperature superconductors. These results were submitted to Appl. Phys. Lett. for publication (Please see Appendix C).

In the Phase II study (of this two-phased program), the technical objectives will be:

- * Improvement in the responsivity of the detector,
- * More complete study of temperature dependence of the response.
- * Wavelength dependence of the response in 1-10 μ region.
- * High frequency or time dependence of the response.
- * Determination of detector noise level (NEP);

PROGRESS MADE IN THE FIRST TWO MONTHS OF PHASE I STUDY:

Laser deposition experiment is conducted in a high vacuum. The vacuum system utilized is Veco VE-400 model equipped with 4" diffusion pump and Precision PS-500 mechanical pump. The vacuum chamber is fitted with appropriate windows to direct the laser beam onto the target. The laser used in this experiment was frequency-doubled or quadrupled pulsed Q-switched Nd:YAG laser (Quantel International) capable of operating at 532 nm or 265 nm with pulse duration ≈ 10 nsec. The laser beam was incident on the target at approximately 45° angle. A quartz lens of long focal length (30-cm) was used to obtain an energy density of $\approx 2 \text{ J/cm}^2$.

The source (target) material was a pellet of high T_c Y-Ba-Cu-O superconductor (2.5-cm in diameter and 2-mm thick). To obtain a uniform deposition rate and avoid texturing, the target pellet was slowly rotated through a rotatory feed through. The MgO and/or ZrO₂ substrate was mounted at a distance of ≈ 3 -cm from the target surface, close to the normal from the center of the laser spot. The vacuum chamber was first evacuated to 10^{-6} Torr and then back filled with 10 mTorr of Oxygen.

The laser was fired at a repetition rate of 10 Hz. With each shot, a plume of intense blue and white light emission could be observed normal to the surface. To incorporate sufficient oxygen during deposition, a jet of oxygen gas was directly introduced into the plume by extending the gas feed through and adjusting the oxygen flow rate to obtain a background pressure of 30-50 mTorr.

The initial deposition was made with substrate at room temperature. A black deposit could be observed on the substrate. However, the film discolored rapidly to brown-yellowish (in minutes) upon exposure. In subsequent experiments, the film was deposited with the substrate heated to 450°C . This resulted in shiny, dark brown film with strong adhesion. After deposition, the film was subsequently annealed in an oxygen atmosphere for 1 hour at 900°C followed by slow cooling at room temperature.

However, it was observed that high temperature annealing tends to percolate microcrystals which renders the optical excitation highly inhomogeneous for optical detection studies. Thus subsequently, thin films were made by plasma assisted laser deposition (PLD) technique invented by Dr. H.S. Kwok group at University of Buffalo. One great advantage of PLD method is that as-deposited thin films of desired thickness can be prepared at low temperature (450°C) without the need of any post annealing. In this method, an additional high voltage (+ 300 V) ring-shaped copper wire is placed in the middle between target and substrate. The target and the electrode form an anode cathode pair and low dc discharge is triggered by laser pulse. Fig.1 shows a typical R-T curve of the film deposited by PLD method indicating an excellent superconducting transition.

PROGRESS MADE IN SECOND TWO MONTHS OF PHASE I STUDY:

Once a high quality thin film is prepared, the next logical step is to produce pattern in these films to convert them into useful devices. In the present work, a dry processing method, namely laser induced etching, was adopted. The pattern is done by a cw, q-switched, frequency-doubled Nd:YAG laser operating at 532 nm at KHz rep. rate.

For patterning, a standard laser trimmer was used. The laser had a pulse duration of 80 nsec, repetition rate of 1 KHz and operating at 532 nm. The laser beam was focused to a diameter of $\approx 20 \mu\text{m}$ by an optical microscope. Initially, a mechanical X-Y stage was used to translate the sample but the edges were found to be quite irregular. Subsequently, in collaboration with Dr. H.S. Kwok group at Institute on Superconductivity (University of Buffalo), two-computer controlled stepper motors were used to translate the sample.

The sample is mounted on a x-y stage controlled by a computer driven stepper motors with step size of $1 \mu\text{m}$. Typical scan rate involved an average macroscopic rate of $100 \mu/\text{sec}$. The laser beam is focused through a 10X microscopic objective onto the film to a spot size of $\approx 20 \mu\text{m}$. Since the stepper motor is computer controlled, we could make very complicated structures. In order to increase sensitivity of the detector, a "zig-zag" shape pattern of $20 \mu\text{m}$ -wide, $0.3 \mu\text{m}$ -thick, and 25-cm long was made on a superconducting film deposited on ZrO_2 . The laser pattern is shown in Fig.2. It was always ascertained that the superconducting transition was not affected by the laser patterning process.

The experimental set-up used in the optical measurement is shown in Fig.3. A pulsed Q-switched Nd:YAG laser was used in the detector measurement. The second harmonic at 532 nm was used primarily because of ease of alignment. A constant current source was used to provide the d.c. bias, and the voltage across the microbridge was monitored with a fast oscilloscope.

Fig.4 shows the time dependence of the optical response near the transition temperature. It was found that only the slow component could be observed at and above the transition temperature. Several groups have observed similar bolometric response on these films. In this mode, detector operates as a bolometer (the radiation simply heating the sample and thereby increasing the resistance) and the response is proportional to the temperature coefficient dR/dT .

Real time response below the transition temperature is shown in Fig.5. It can be seen that below the transition temperature, the response is relatively faster. The temporal response time is limited by the incident laser pulse-width. Note that the response is measured well below T_c where the slope of $R(T)$ is not maximum.

PROGRESS MADE IN THE LAST TWO MONTHS OF PHASE I STUDY:

It is obvious that non equilibrium behavior in the superconductor depends critically on the quality and method of preparation of thin film samples. Our previous results indicated that the most important design criteria for successful observation of optical detection is that the film should be optically thin for the particular radiation. It is because that quasiparticle generation occurs within the within the absorption depth α^{-1} , where α is absorptivity.. If the film is optically thick and since the recombination time of the quasiparticle is much faster than the diffusion time, the nonequilibrium response will be short-circuited by the superconductivity in the dark portion of the film. Thus in our subsequent experiments, smooth, transparent 80 nm thin films were used. Depending on the film thickness and the deposition condition, T_c could vary from 41°K to 82°K . Preliminary results showed that the low T_c films provided better optical response. For the present experiment 41°K T_c films were used. For detection experiments, $1.06 \mu\text{m}$ infrared beam with 6 nsec pulse duration was utilized.

In the first set of measurements the resistivity of the microbridge was recorded at various bias currents. Fig. 6 shows the temperature dependence of the resistivity at a bias current of 0.1 mA (squares) and 1.0 mA (circles).

Fig.7 shows the electrical output of the samples for 3 different temperatures (5K, 25K, 32K) at a laser fluence of $200 \mu\text{J}/\text{cm}^2$ and a bias current of 1.0 mA. It can be seen that below T_c only a fast response of 15 nsec duration is observed. The temporal response time is limited mainly by the resolution of the digitizer. At temperatures near T_c , a slow component can then be seen, superimposed on the fast component. It becomes the only component above T_c . The decay of the slow component is nonexponential, but resembles the error function-like decay characteristics of thermal diffusion.

The slow component is evidently due to thermal heating of the film. The decay time is simply due to cooling of the film by heat diffusion into the substrate. Fig.8 shows the temperature dependence of the slow component. This temperature dependence agrees very well with the 0.1 mA dR/dT curve shown, which is derived from the low bias curve in Fig.6. It bears the same characteristics of the bolometric response observed by other authors.

The fast component is clearly nonthermal in origin. Fig.9 shows the peak of the fast response pulse as a function of temperature, at a bias current of 1.0 mA. The higher bias current is not essential in observing the fast signal, but provides a better signal to noise ratio in the measurement. In Fig.4, it can be seen that the signal remains constant at temperature well below the superconducting transition where dR/dT is zero, and drops to zero at T_c . The response is non-thermal in the sense that it does not follow the dR/dT dependence. In our Phase II study, the ultimate speed of the fast response component will be investigated with a picosecond laser system.

The observed voltage shift due to the incident optical power is shown in Fig. 10. Responsivity can be derived from the ratio of output voltage to incident optical power. From this relation, the observed YBaCuO detector responsivity is 0.6 V/W at 100 MHz. While the measured detector parameters are below the state of the art, further improvement can be expected by patterning the thin film to increase the normal state resistant and by thinning the films. Theoretical estimation of the responsivity of the proposed detector indicates a value of 10^4 V/W at 10 GHz. Recently, a slow bolometric response of these detectors have been reported to be in the range of 10^3 V/W. Thus there are reasons to believe that these new materials will make a technological impact.

FUTURE EXPERIMENTS FOR PHASE II:

At present, we do not know whether there is any correlation between the observation of nonthermal response and poorer T_c of the patterned films. Unlike the granular films used in other experiments, the films used here were optically smooth with $< 0.2 \mu\text{m}$ roughness. Obvious, much remains to be done concerning this particular aspect of the film preparation before nonequilibrium optical response can be understood. While our results clearly point to a non-bolometric (NB) response, several issues remain:

* Even though the film is smooth and continuous, are the grain boundaries (GB) responsible for NB response? It is claimed that granularity of the film is important for the NB response. It is an important issue because granularity generally depresses the T_c of the superconductor. The critical question relevant to practical application is; will a perfect 90K Y-Ba-Cu-O film, or a 125K Tl-Ba-Cu-O film show NB response? If the NB response is only associated with low T_c films, then its usefulness will be limited.

* What is the physics of the NB response in HTS materials? Is it the same as in other metallic superconductors? Clearly more experiments are needed to provide more data to develop a fuller understanding before such effects can be applied.

In Phase II, we will try to answer these issues. In addition, the following studies will be conducted:

- * Improvement in the responsivity of the detector
- * More complete study of temperature dependence of the response.
- * Wavelength dependence of the response in 1–10 μ region.
- * High frequency or time dependence of the response.
- * Determination of detector noise level (NEP).



Fig.1. Temperature dependence of the resistivity at a bias current of 20 μ A showing the transition temperature at 90 K.

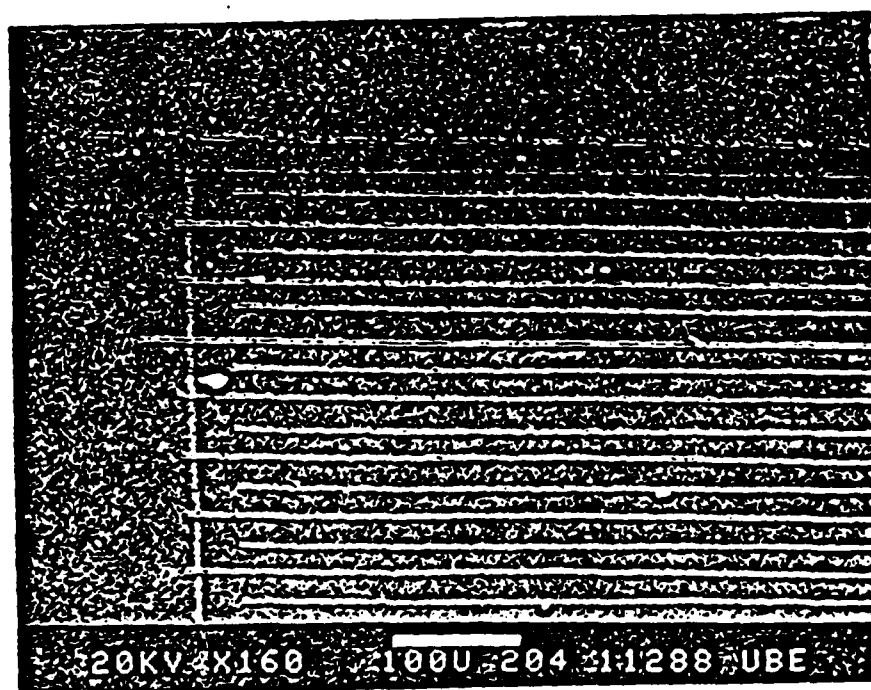
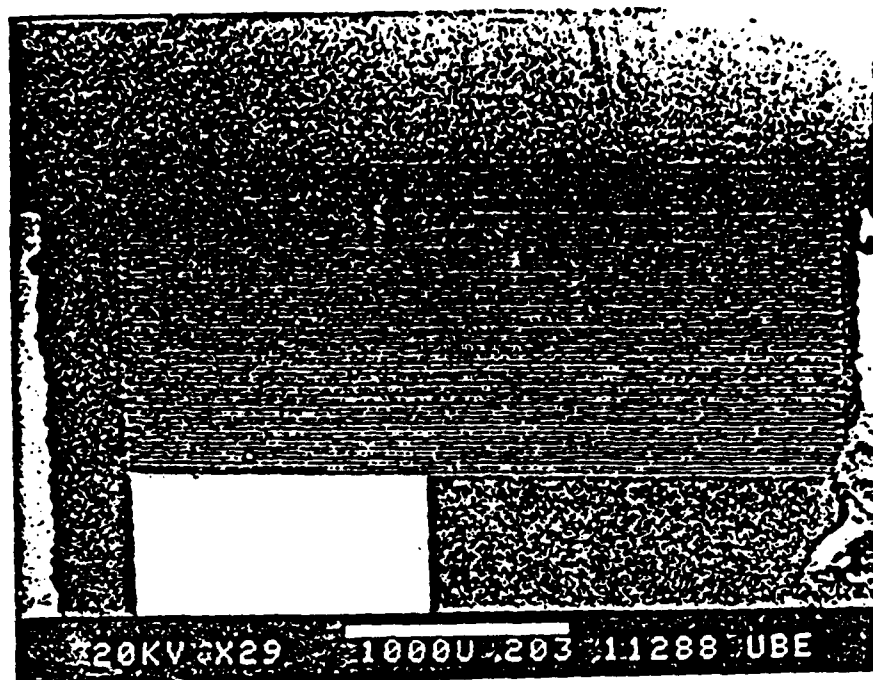


Fig.2. The pattern made by laser writing on a superconducting thin film.

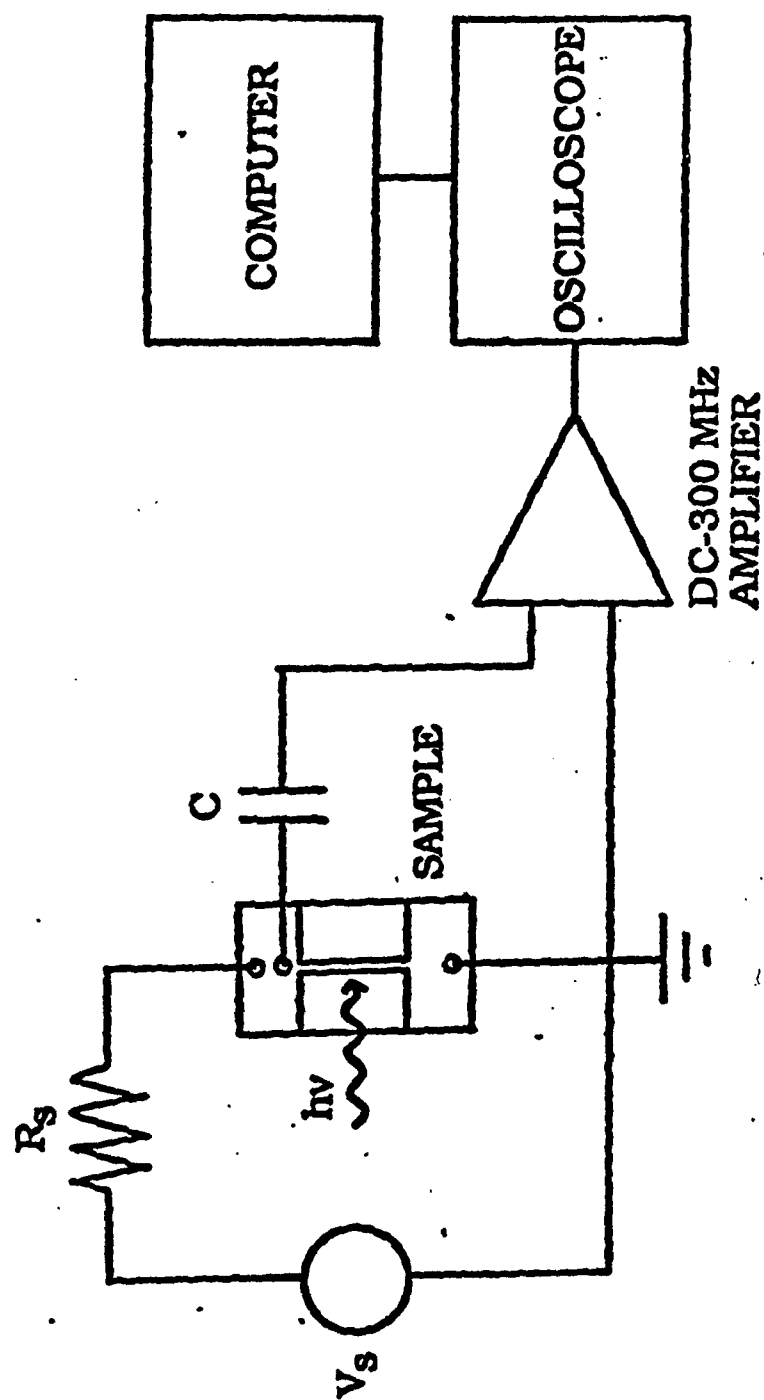


Fig. 3. Block diagram of exptal set-up used for optical detection.

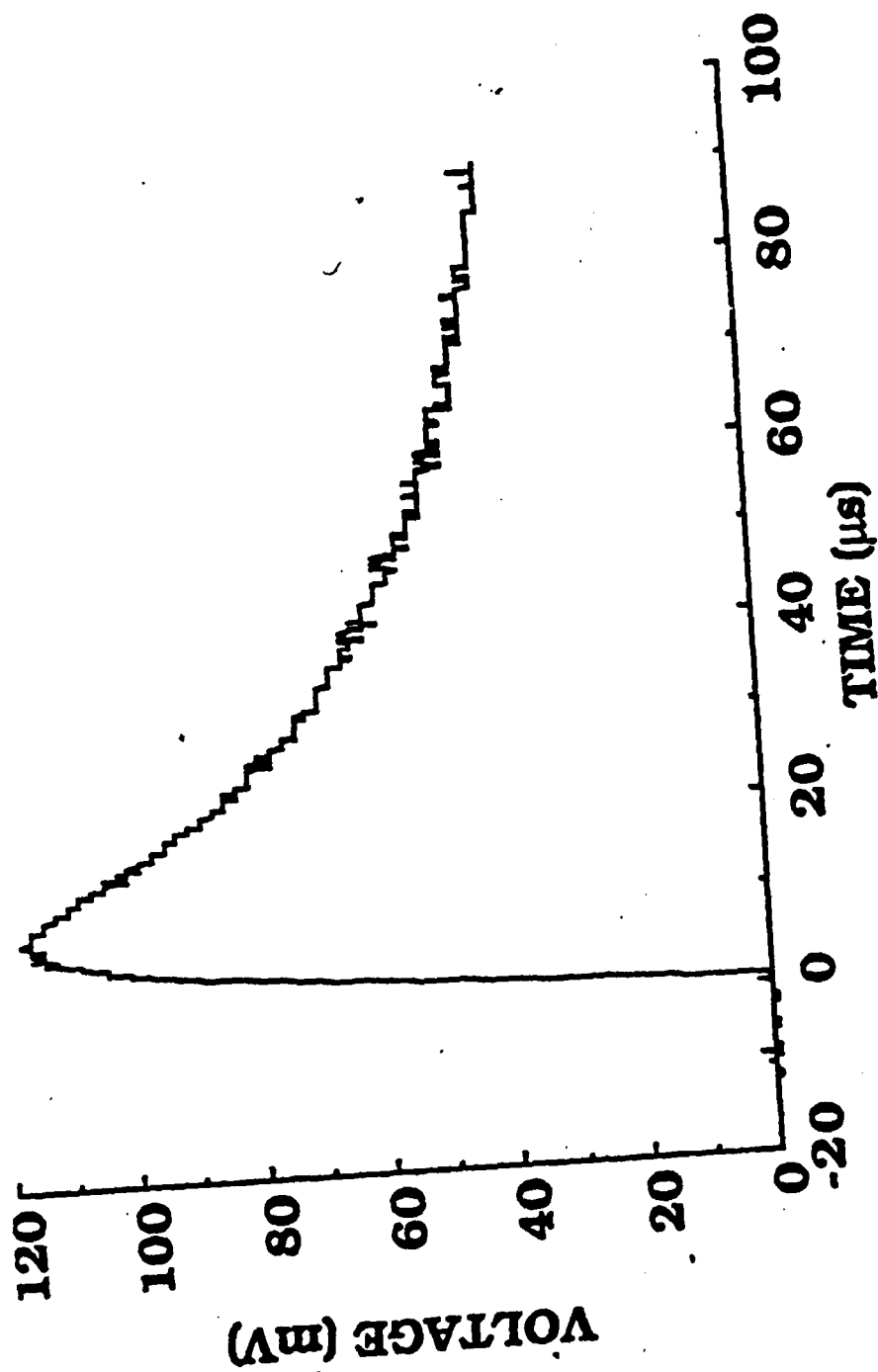


Fig.4. Real time response of the detector above transition temperature.

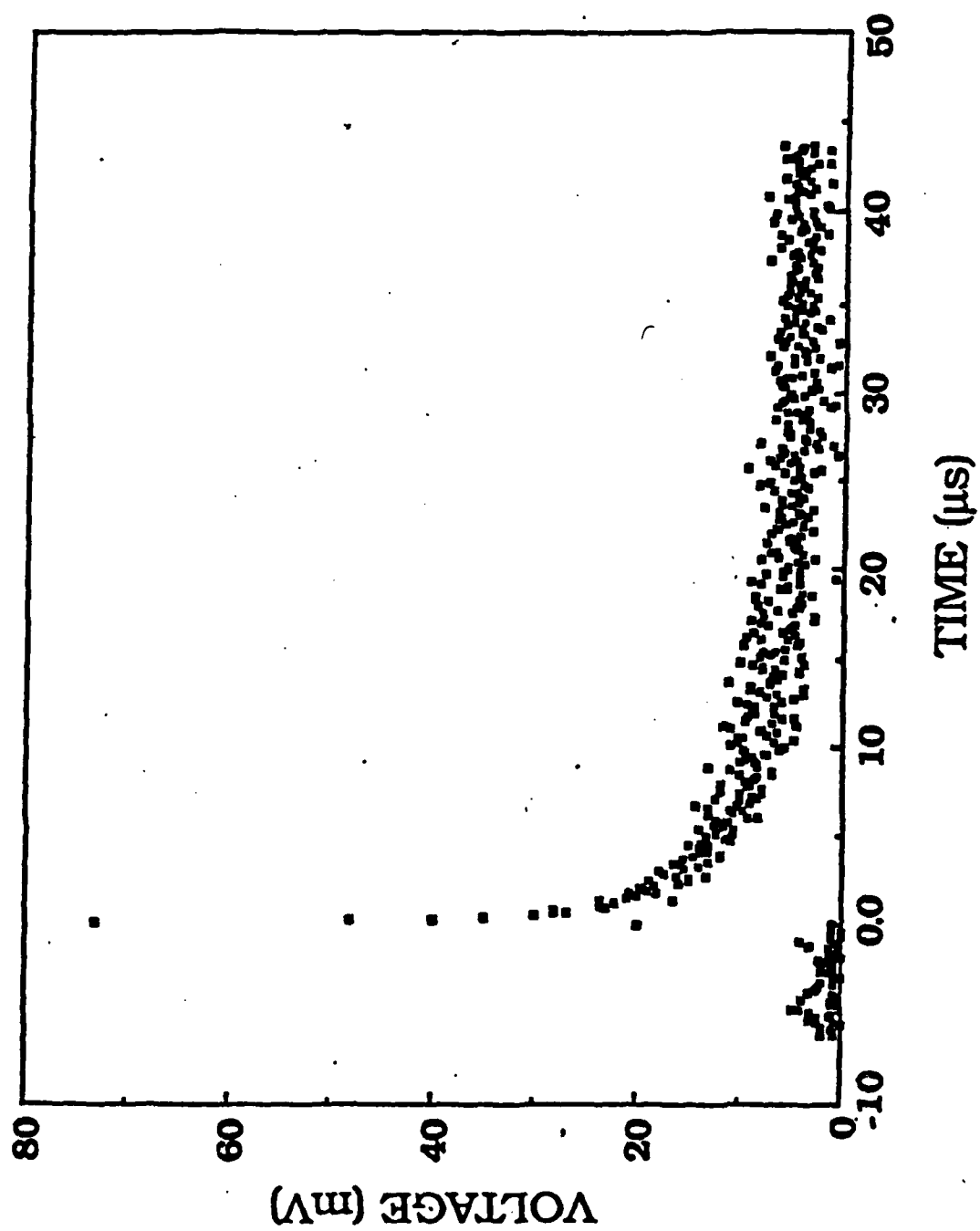


Fig.5. Real time response of the detector below the transition temperature.

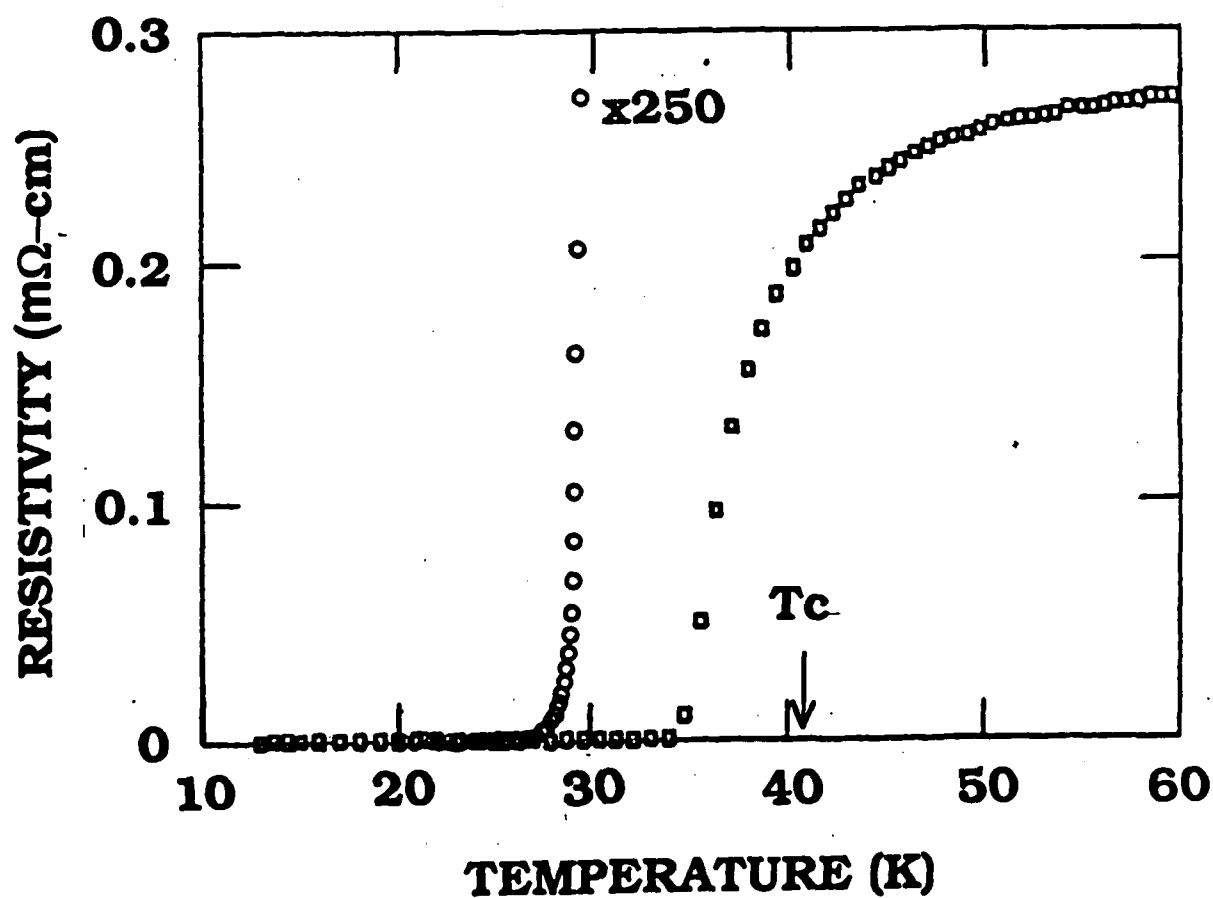


Fig.6. Temperature dependence of the resistivity for a semitransparent 41^0K film at a bias current of 0.1 mA (squares) and 1.0 mA (circles).

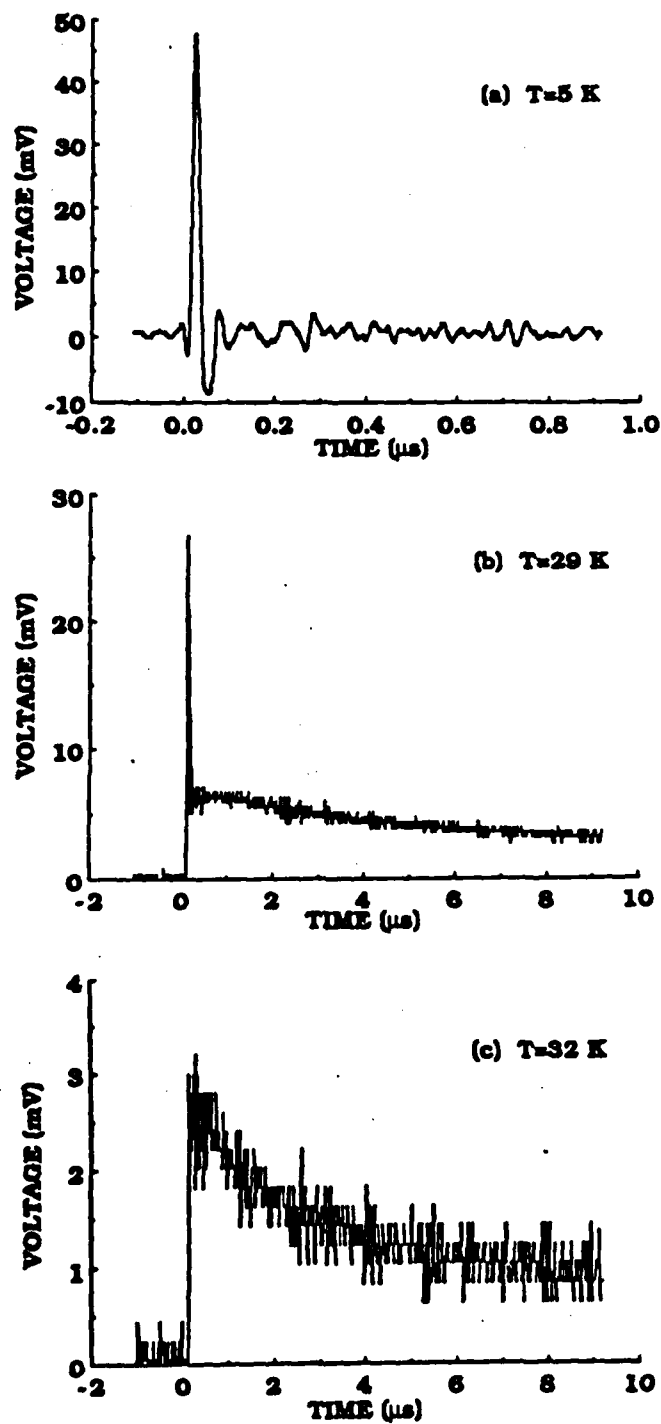


Fig.7. Temporal voltage response of the microbridge at (a) 5K, (b) 28K, (c) 32K, at a bias current of 1.0 mA.

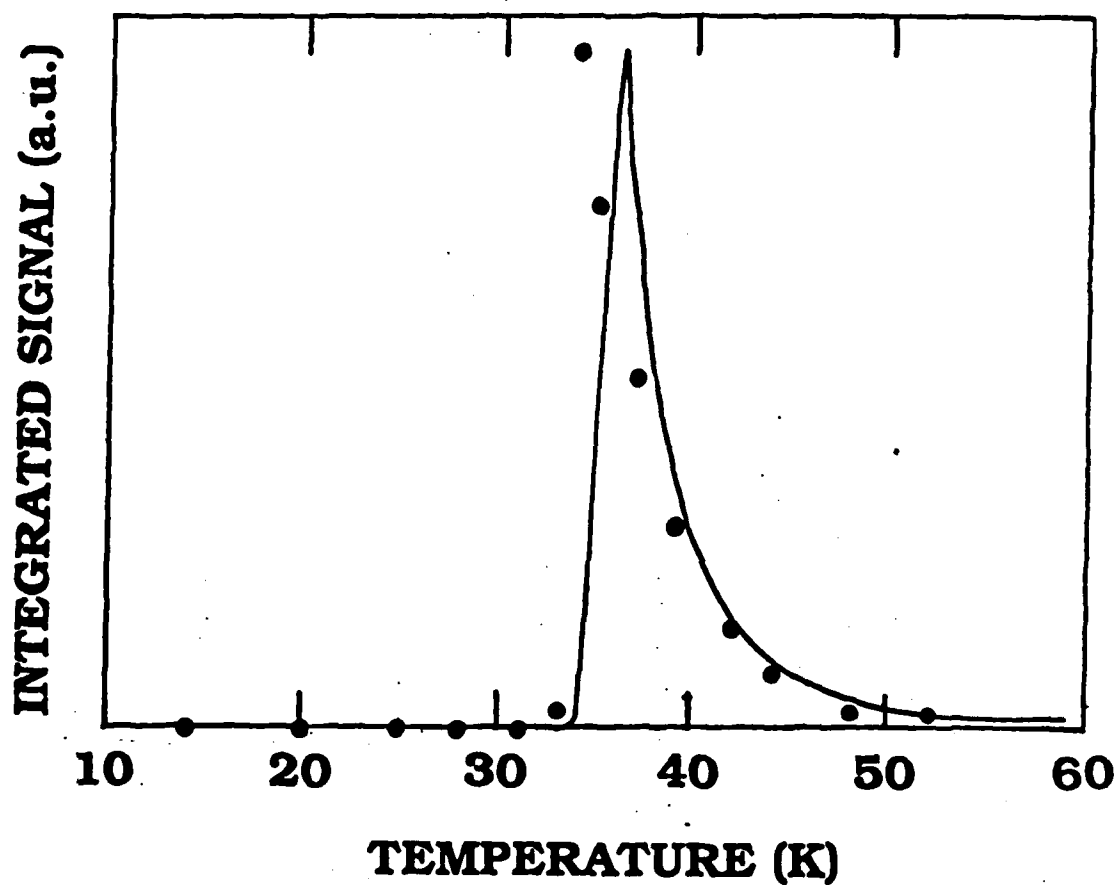


Fig.8. A comparison of the temperature dependence of the slow response (data points) and the dR/dT curve obtained from Fig.6.

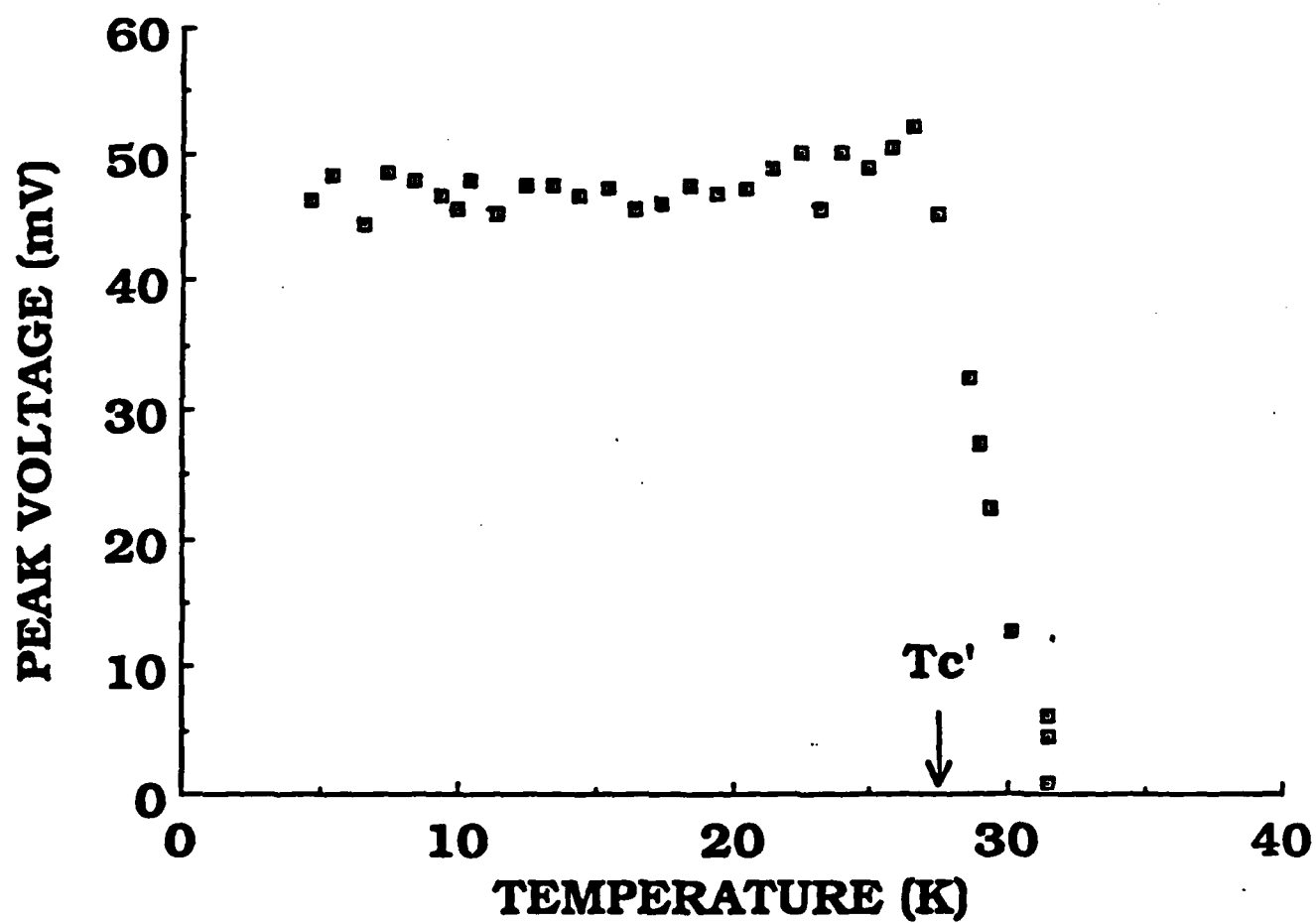


Fig.9. Temperature dependence of the fast nonthermal response. T_c is at 30K at the 1.0 mA bias.

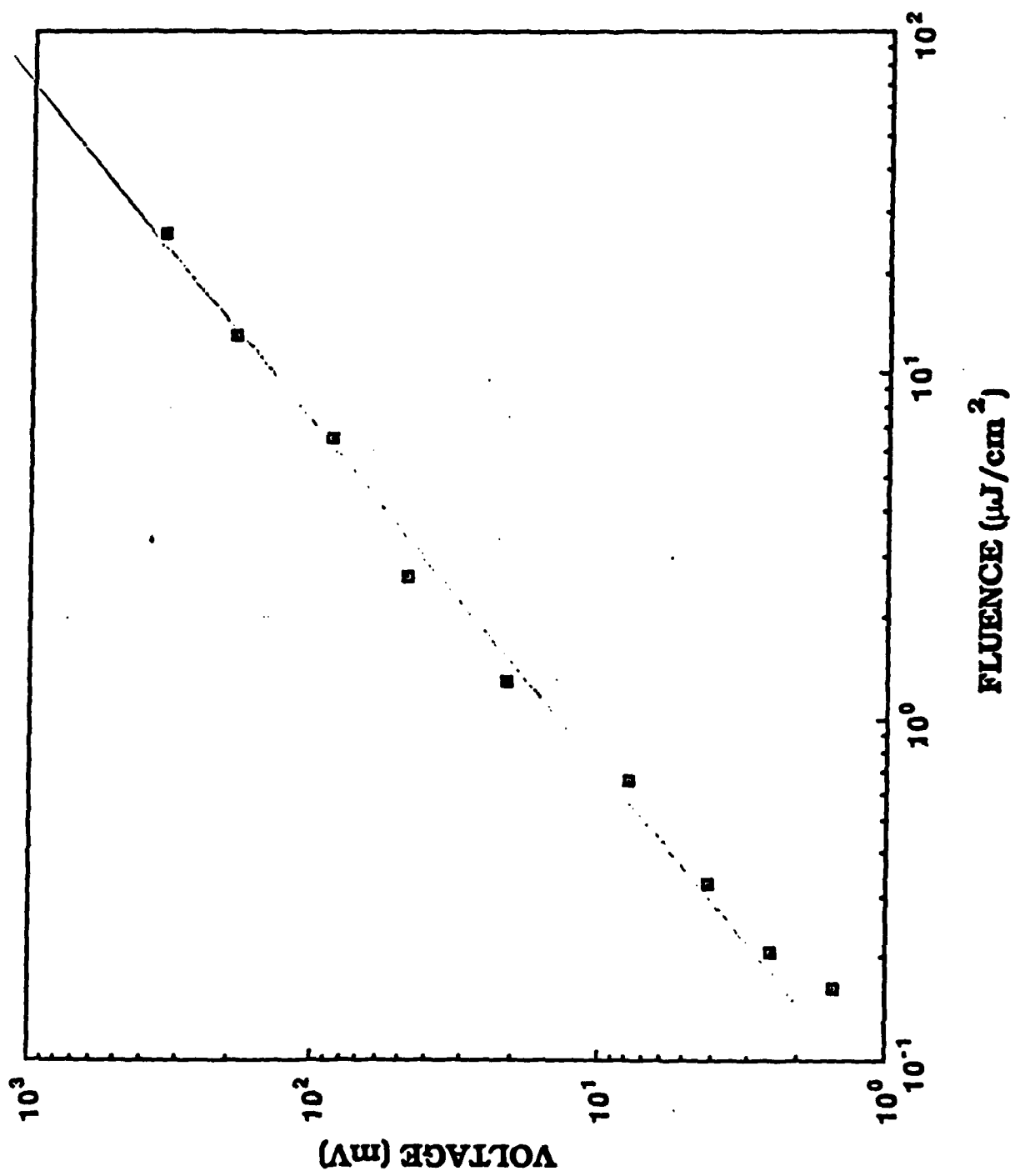


Fig.10. Relation between incident optical radiation and output voltage.

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